STABILISATION OF THE CERN-PS HEAD-TAIL INSTABILITIES BY LINEAR COUPLING

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STUDY OF THE CERN-PS BEAM FOR LHC

Single bunch of protons with nominal intensity : $N_b \approx 10^{12}$

500 ms long flat bottom at the injection kinetic energy :

$$E_c = 1.4 \text{ Gev}$$

Bunch length : $\tau_b = 160 \text{ ns}$

Transverse tunes : $Q_h = 6.18$ $Q_v = 6.21$

Transverse chromaticities : $\xi_x \approx -0.9$ $\xi_y \approx -1.3$

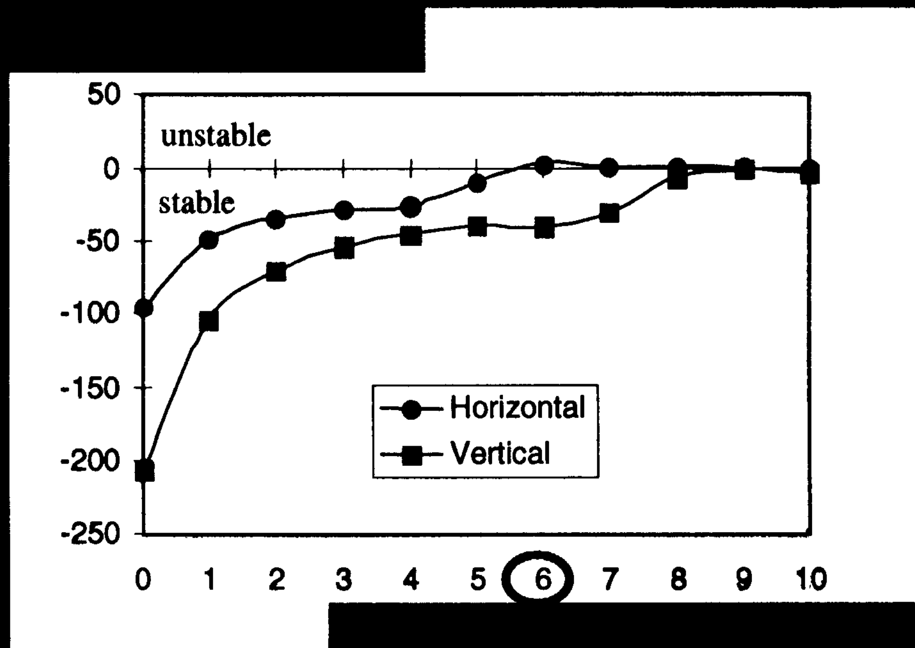
THEORY (1/2)

Single-bunch instability ⇒ classical Sacherer's formula

$$\Delta\omega_{c,m}^{x,y} = \left(|m| + 1 \right)^{-1} \frac{j\, e\, \beta\, I_b}{2\, m_0\, \gamma\, Q_{x0,y0}\, \Omega_0\, L} \frac{\sum\limits_{k=-\infty}^{k=+\infty} Z_{x,y}\left(\omega_k^{x,y} \right) h_m\left(\omega_k^{x,y} - \omega_{\xi_{x,y}} \right)}{\sum\limits_{k=-\infty}^{k=+\infty} h_m\left(\omega_k^{x,y} - \omega_{\xi_{x,y}} \right)}$$

$$\omega_k^{x,y} = \left(k + Q_{x0,y0} \right) \Omega_0 + m\, \omega_s$$

$$-\infty \le k \le +\infty$$



THEORY (2/2)

Stabilising mechanisms

Landau damping $$\Delta\omega_{\mathrm{HWHH}}^{x,y} \geq \sqrt{3}\left|\Delta\omega_{c,m}^{x,y}\right|$$

Coupling

$$\left|\underline{K}_0\right| \geq \frac{2\left[-Q_{x0}\,Q_{y0}\,V_{\mathrm{eq}x}^{m}\,V_{\mathrm{eq}y}^{m}\right]^{1/2}}{R^2\,\Omega_0} \times \frac{\left[\left(V_{\mathrm{eq}x}^{m}+V_{\mathrm{eq}y}^{m}\right)^2+\Omega_0^2\left(Q_h-Q_v\right)^2\right]^{1/2}}{-\left(V_{\mathrm{eq}x}^{m}+V_{\mathrm{eq}y}^{m}\right)}$$

$$V_{\mathrm{eq}x}^{m}+V_{\mathrm{eq}y}^{m} \leq 0$$

$$V_{\mathrm{eq}x,y}^{m} = -\mathrm{Im}\left(\Delta\omega_{c,m}^{x,y}\right)$$

$$Q_{h,v} = \left(\omega_{x0,y0}+U_{\mathrm{eq}x,y}^{m}\right)/\Omega_0$$

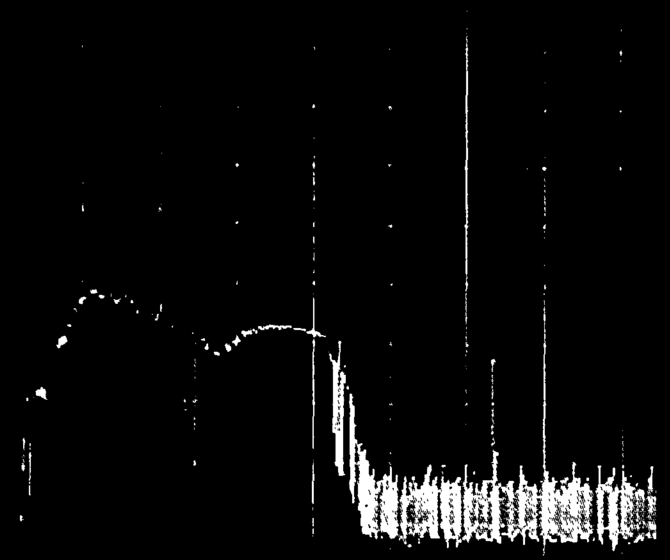
$$U_{\mathrm{eq}x,y}^{m} = \mathrm{Re}\left(\Delta\omega_{c,m}^{x,y}\right)$$

Coupled Landau damping

OBSERVATIONS (1/8)

Single-bunch instability

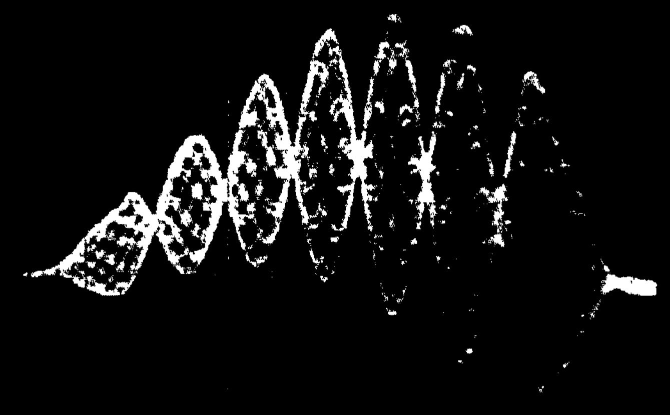
Spectrum Analyzer
(zero frequency span)



RES BW 10 kHz   VBW 3 kHz   SWP 1.2 s

rise time $\approx 30\,\text{ms}$

Beam-Position Monitor
(20 revolutions superimposed)



OBSERVATIONS (2/8)

Damping

Stabilisation by Landau damping

I_{oct}^{exp} [A]	I_{oct}^{theory} [A]	$\left\lvert I_{oct}^{exp} [A] / I_{oct}^{theory} [A] \right\rvert$
8	6.8	1.2
-10	6.8	1.5

⇒ No emittance blow-up during the first 500 ms :

$$\left(\varepsilon_x^{\mathrm{norm},1\sigma} + \varepsilon_y^{\mathrm{norm},1\sigma}\right) / 2 \approx 2\,\mu\mathrm{m}$$

OBSERVATIONS (3/8)

Stabilisation by coupling

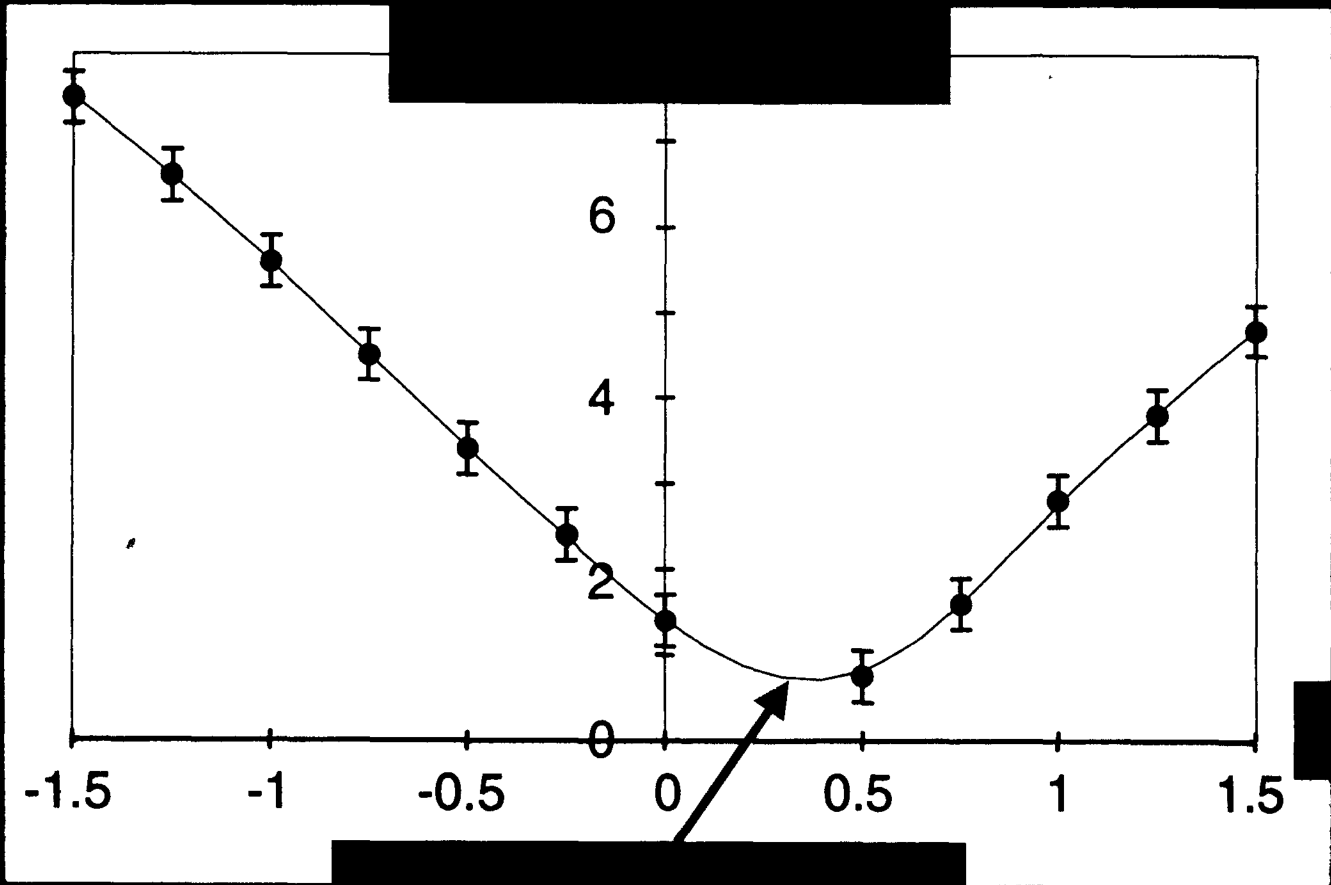
I_{skew} [A]	$\lvert \underline{K}_0 \rvert^{\text{exp}} (10^{-5})[\text{m}^{-2}]$	$\lvert \underline{K}_0 \rvert^{\text{theory}} (10^{-5})[\text{m}^{-2}]$	$\lvert \underline{K}_0 \rvert^{\text{exp}} / \lvert \underline{K}_0 \rvert^{\text{theory}}$
0.73	1.7	1	1.7
-0.07	1.7	1	1.7

⇒ No emittance blow-up during the first 500 ms :

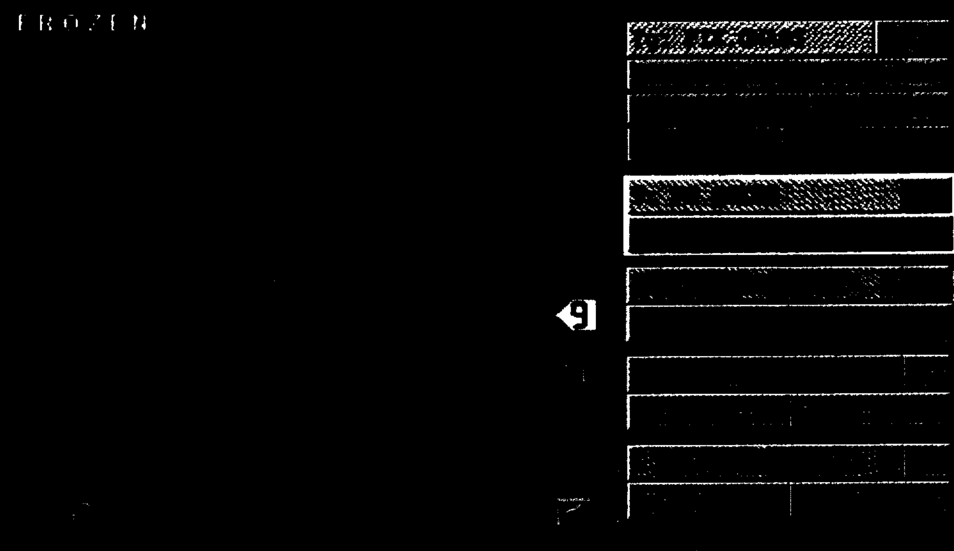
$$\left(\varepsilon_x^{\text{norm},1\sigma} + \varepsilon_y^{\text{norm},1\sigma}\right) / 2 \approx 1.9\,\mu\text{m}$$

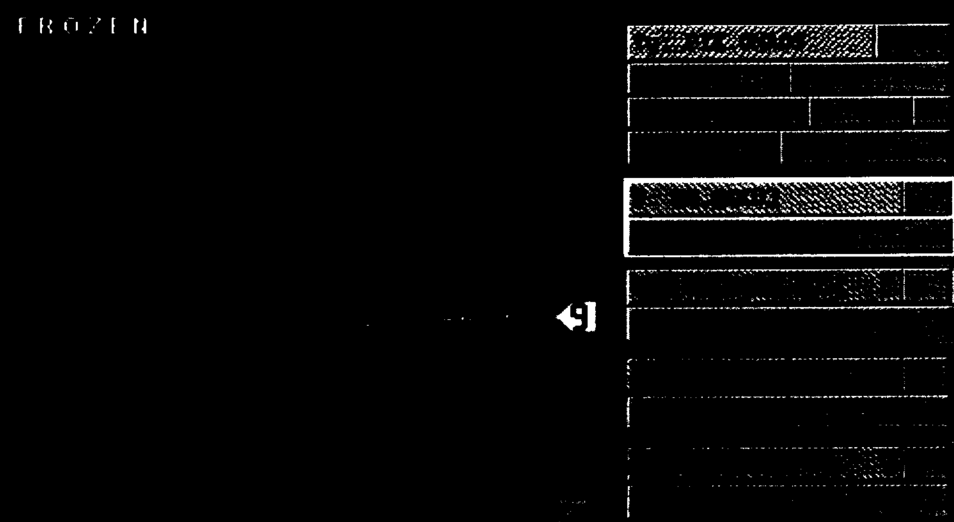
OBSERVATIONS (4/8)

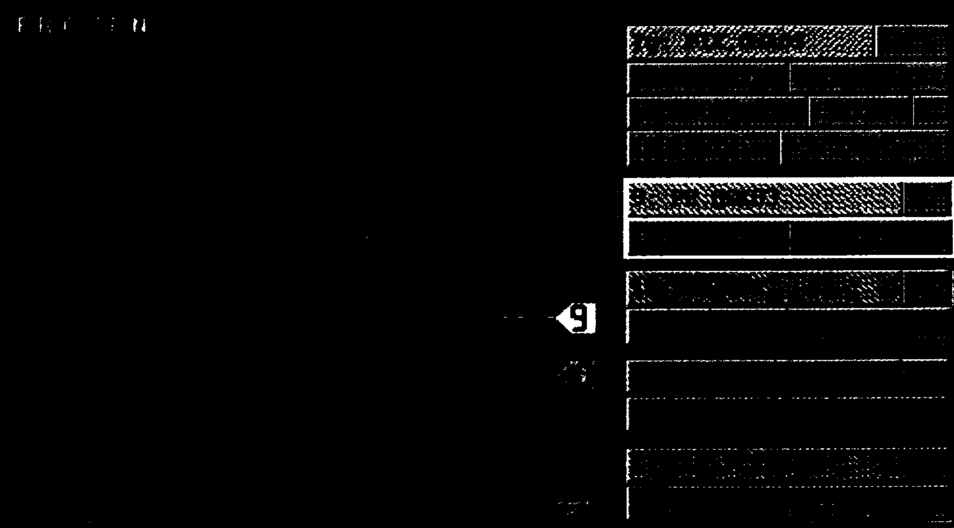
Modulus of the normalised skew gradient vs. skew quadrupole current



OBSERVATIONS (5/8)







OBSERVATIONS (6/8)

Single bunch of protons with ~ultimate intensity : $N_b \approx 1.8 \times 10^{12}$

The transverse coherent frequency shifts are multiplied by 1.8

Damping

- Stabilisation by Landau damping

$I_{oct}^{\exp}$ [A]	I_{oct}^{theory} [A]	$\left\| I_{oct}^{\exp} [\text{A}] / I_{oct}^{\text{theory}} [\text{A}] \right\|$
6	12.2	0.5
-9	12.2	0.7

⇒ No emittance blow-up during the first 500 ms :

$$\left(\varepsilon_x^{\text{norm},1\sigma} + \varepsilon_y^{\text{norm},1\sigma}\right) / 2 \approx 3.4\,\mu\text{m}$$

OBSERVATIONS (7/8)

- Stabilisation by coupling

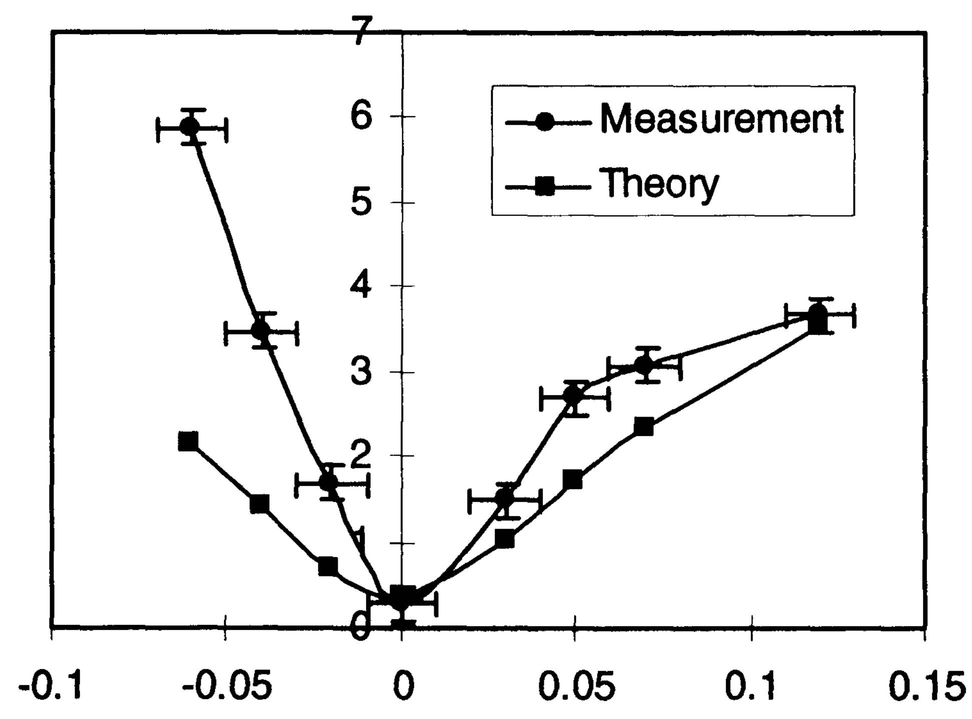
$I_{skew}\,[\mathrm{A}]$	$\lvert \underline{K}_0 \rvert^{exp} (10^{-5}) [\mathrm{m}^{-2}]$	$\lvert \underline{K}_0 \rvert^{theory} (10^{-5}) [\mathrm{m}^{-2}]$	$\lvert \underline{K}_0 \rvert^{exp} / \lvert \underline{K}_0 \rvert^{theory}$
0.68	1.5	1	1.5
-0.02	1.5	1	1.5

⇒ No emittance blow-up during the first 500 ms :

$$\left(\varepsilon_x^{\mathrm{norm},1\sigma} + \varepsilon_y^{\mathrm{norm},1\sigma}\right) / 2 \approx 3.2\,\mu\mathrm{m}$$

OBSERVATIONS (8/8)

- Stabilisation using both skew quadrupoles and tune separation



PREDICTIONS

8 bunches of protons with nominal intensity : $N_b \approx 10^{12}$

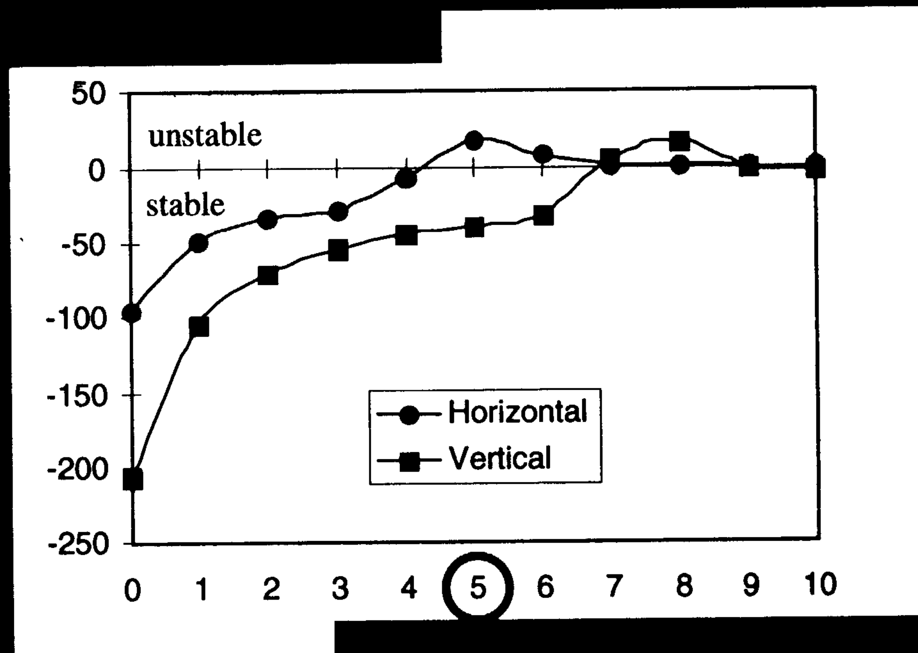
⇒ coupled-bunch instabilities

Theoretical stabilising skew gradient

$$\left|\underline{K}_0\right|^{\text{theory}} = 4.3 \times 10^{-5}\ \mathrm{m}^{-2}$$

⇒ $I_{skew} \leq -0.75\,\mathrm{A}$

or $I_{skew} \geq 1.4\,\mathrm{A}$



The same result is obtained for the ~ultimate beam

CONCLUSION

The high-order head-tail instabilities of the CERN-PS beam for LHC (single bunch with nominal or ultimate intensity) CAN BE DAMPED using coupling only (skew quadrupoles and/or tune separation)

The coupled-bunch instabilities SHOULD BE DAMPED also by coupling only

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